

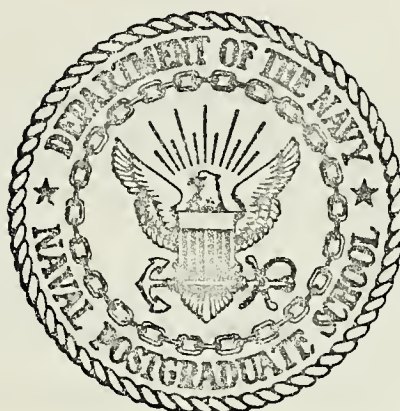
ORIGIN AND DEVELOPMENT OF BEACH CUSPS AT
MONTEREY BAY, CALIFORNIA

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NAVAL POSTGRADUATE SCHOOL

Monterey, California



THESIS

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MONTEREY BAY, CALIFORNIA

by

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by

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Lieutenant Commander, United States Navy
B.S., State University of New York, Maritime College, 1962

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ABSTRACT

Beach cusps were observed daily on Del Monte Beach and measurements obtained so that a quantitative description of the parameters which affect formation and size of cusps could be determined. In addition a theory of cusp formation was formulated and an insight obtained into the factors which influence the shape and size of cusps throughout their lifetime. Finally, the events leading to cusp destruction were examined.

It was determined that beach cusps are depositional in nature, forming most easily in coarse, loose sediment. Cusp development commences at a rise or area of accretion on the beach. A series of beach cusps forms sequentially rather than simultaneously.

The width of beach cusps are a function of wave height; the larger waves producing wider cusp spacing. Uniform spacing of cusps in a series can be attributed to the same size waves striking the beach during the formation period of the cusps.

Once formed, cusps are stable and tend to maintain their dimensions unless a large change in wave or beach condition occurs.

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I. INTRODUCTION

A. DESCRIPTION OF PROBLEM

Throughout the past century, many papers and articles have been written concerning beach cusps. Although cusps can form with many modifications to the basic shape, most observers describe them as regular, crescent-shape forms which frequently appear on the surface of the beach. Cusps have been noted to form in many types and sizes of sediments from fine sand to large cobblestones [Johnson, 1909] and even large boulders [Butler, 1937]. A series of typical beach cusps which were formed along Del Monte Beach on Monterey Bay are shown in Fig. 1. A typical cusp consists of two raised horns inclined towards the water. The horns are roughly triangular in shape with the points or apices directed seaward. In general, the top of a horn is built-up to a level higher than the surrounding undisturbed beach. The area between the horns is eroded away such that an embayment is formed. The back or shoreward side of both the horns and bays are connected to and blend into the beach berm.

The origin of cusps has baffled observers on both lake and ocean beaches. Many theories have been presented concerning the origin and dynamics of beach cusps, but none have been universally accepted as a satisfactory solution. The mechanisms which cause cusp formation as well as the factors which influence the size and shape of beach cusps are not well known. Similarly the factors leading to the destruction of beach cusps have not been agreed upon.



Figure 1. Ideal Beach Cusps Which Frequently Form Along Monterey Bay Beaches.

B. OBJECTIVES

As described by Dolan and Ferm [1968] there is a hierarchy of cusp sizes varying in width from 2300-4900 ft (700-1500 m) to only a few centimeters (inches). The cusps observed and analyzed in this study were medium sized cusps of from 33-213 ft (10-65 m) in width. These correspond to Evans' [1938] "ideal" cusps. All the cusps from which data were obtained and which are documented in this thesis were formed in ocean beach sand.

It is the purpose of this thesis to present a theory of formation of these moderate size sand cusps. The parameters which affect the formation and size of the cusps will be qualitatively discussed. A quantitative description of some of the major parameters which determine cusp size will be presented. The stability of the shape of the cusps and the forces which influence the shape and size of the cusps throughout their lifetime will be discussed. Finally, the events leading to cusp destruction will be examined.

C. REVIEW OF THE LITERATURE

Jefferson [1899] described cusps on cobble beaches having spacings of 20-30 ft (6-9 m). He ascribed their formation to seaweed piled on the beach modifying the actions of the great waves. His definition of a great wave was one which overtopped the average in height and extent of advance up the beach. According to Jefferson, at intervals of approximately ten minutes, a great wave would break evenly upon a beach on which a line of seaweed had been deposited. The breaking wave sent tons of seawater over the cobblestones above the line of seaweed. Immediately after breaking, the wave retired leaving considerable masses of water behind the seaweed. This water could only escape through occasional breaks in the seaweed and at these

points the considerable rush of water seaward through the break area scoured out the bay of the cusps.

The problem with Jefferson's theory of cusp development was that cusps frequently form on beaches where there is no line of seaweed or other barrier to uprush of the waves. In addition, his theory did not explain the regularity of cusp spacing which is normally observed in a series of cusps.

Another early observer of beach cusps, Branner [1900], concluded that cusp formation was due to the interference of two sets of interfering waves interacting with each other where they converge upon the shore. According to this line of reasoning, there is a tendency for the waves to destructively interfere with each other along the lines of interference and to heap up the sands at these points. At points of non-interference, the waves diverge and throw the beach sands and all floating material alternately left and right.

Branner's theory has been refuted by Johnson [1909] who points out that under natural conditions one could not expect the lines of interference between two sets of waves to strike the beach at the same point twice in succession. He, in fact, states that the presence of parallel waves is one of the physical conditions necessary for cusp formation. One might surmise then that a set of intersecting waves at a beach actually hinders the formation of cusps.

Johnson, in addition to refuting the theories of Branner and others, developed a comprehensive theory of origin of beach cusps and described many of the details of the physical parameters associated with cusps. The factors which he considered significant in determining the spacing between cusps were wave height and possibly beach slope. As wave height

increased, cusp spacing was found to increase also. Johnson suggests that doubling the height of waves close to the shoreline results in a doubling of cusp spacing. He found that, in general, within a series of cusps, the spacing or distance between individual cusps was somewhat regular. Where both fine and coarse material were present the cusps were built of the coarser material. According to Johnson, in order for cusps to form properly, the wave fronts of cusp forming waves must be nearly parallel to the beach. He also believed that cusp origin was associated with irregularly spaced depressions in the beach. Selective erosion by the swash developed from initial depressions in the beach, shallow troughs of approximately uniform breadth. The ultimate size of these troughs was proportional to the size of the waves, and determined the relatively uniform spacing of the cusps which developed on the intertrough elevations. Growth of the depressions or channels reached a limit whenever the tendency toward growth imposed on the more favorable channels no longer was sufficient to overcome the tendency of their neighbors to enlarge. Equilibrium was established when adjacent channels were of approximately the same size and at the same time of a size appropriate to accommodate the volumes of water traversing them.

Wave tank experiments were conducted by Escher [1937] in order to attempt to determine the origin of beach cusps. Escher obtained cusp-like features on a laboratory beach composed of sand. He postulated that a standing wave situated along a wave crest which was parallel to the beach would produce areas where greater or less erosion would occur. The spacing of the cusps produced would vary depending upon the wave number of the standing wave. The major shortcomings of Escher's theory were

that the features which he observed in the wave tank were not true cusps and that there was no observational evidence on real beaches to substantiate his theory.

Another early observer of cusp formations was Butler [1937]. Butler observed and reported on cusps formed on a boulder beach at Lake Olga, Quebec. These cusps, with an average spacing of approximately 18 ft (5.5m), were thought by Butler to have been formed as a result of selective erosion of the boundary glacial till present on the beach by swash from average sized waves striking the beach. An unusual feature of these cusps was the size of the material in the cusps, which varied from that of a pea to 3 ft in diameter, with the greatest volume of fragments having diameters of 1 ft or more. Butler listed the factors relating to cusp spacing as wave height of the average waves striking the beach and the size of the component material which made-up the cusps. Butler's theory was not general in that it was only applied to the cusps at Lake Olga and additionally, did not adequately explain the regularity of cusp spacing normally observed.

Evans [1938] described beach cusps composed of sand up to 600 ft (183m) in width. He developed a classification system for various types of cusps found along the shores of lakes and oceans. These were;

- (1) Storm cusps - up to 600 ft (183m) in width
- (2) Ridges of sand on lake bottoms
- (3) Deposition and erosion due to obstructions on the beach
- (4) Very small cusps due to "slop" of a dead sea
- (5) Ideal cusps

With regard to "ideal cusps", Evans [1938, p.621] stated;

"The conditions of adjustment between waves and the shore under which these cusps form are very delicate, and there is very little latitude of action in the process."

He believed that whenever the proper conditions were present, formation was very rapid, almost instantaneous. It was also his contention that once a cusp had formed, a considerable change in wave condition was required to obliterate it. Initially, Evans postulated that beach cusps were originated by the swash breaking through a beach ridge (a long obstruction parallel to the shoreline). Cusps formed preferentially in recently built beach ridges which had been broken through by the waves. A very close adjustment existed in the relationship between height and uniformity of waves and that of the height and shape of the ridge on which it acted.

The regularity in spacing of these cusps (ideal) was attributed to the fact that the initial breaks in the sand ridge were due to a single wave which was larger than those which had built the ridge. According to Evans [1938, p. 622];

"Now a wave is not of the same height throughout its length, but varies somewhat, and there is some regularity in this variation. Again the parabolic swirl of the water when it comes into the openings made by the wave tends to give a regular spacing to the indentations and projections. If two small openings happen to be very close together, they are likely to become one larger opening, while an opening that is slightly too wide will be partly filled with material washed from the adjoining incipient cusps. The completion of the process is dependent on the continuance for a short time of waves of the same size and character as the one which caused the original breaks."

In a later paper, Evans [1945] modified his early theory of formation to include a more complete explanation of the regularity of spacing between cusps. After the waves broke through the sand ridge, which Evans considered necessary for cusp formation, the parabolic swash and backwash carved out a system of bays and horns. This process continued until equilibrium was obtained with all cusps being relatively the same size.

Although Evans' theory provided an explanation for the regularity of spacing of ideal beach cusps, it did not provide an explanation for the formation of cusps on a flat beach where no ridges were present.

A theory similar to that of Johnson [1909] was developed by Kuenen [1948]. He noted that the horns were depositional areas where the material being removed from the bays was deposited. This fact was a key factor in his theory of cusp origin. In Kuenen's theory, as in Johnson's, cusp growth commenced at natural depressions in the beach. Refraction of the swash as it swept into the embayments and fanned out onto the sides of the protruding horns was an essential element in the production of cusps. This caused sediment to be washed sideways out of the troughs onto the horns. Larger material tended to accumulate on the horns while finer material was carried away. As long as the depth of water sweeping through the embayments was so small that the amount of water passing in and out of the bay was able to carry the sediment along, enlargement both vertically and horizontally of the bays continued. As a result, the channel became deeper and wider with steeper sides. When the outer portion of the embayment reached a certain limiting depth, erosion tapered off.

The horns were built-up due to refraction of the swash in the embayments and transport of material towards the sides of the bays. Coarse material tended to be pushed back up the beach of the embayment and out along the developing cusps. When the maximum depth in the central area of the bay had been attained, the growth of the bays and horns gradually decreased.

Because of the closeness of the developing bays a rivalry frequently developed between two cusps attempting to expand. Eventually, however,

equilibrium was established wherein the growth potential of all cusps was essentially satisfied. The water flow in an embayment as described by Kuenen is shown in Fig. 2.

Kuenen's description of the mechanism causing horn growth or accretion is based on a water flow pattern which appears to be in disagreement with that observed by other researchers and this author.

Longuet-Higgins and Parkin [1962] were stimulated to conduct research concerning beach cusps by the idea that construction of the cusps might be due to the occurrence of "edge waves" of the type that can occur in the neighborhood of a sloping beach. Edge waves are widely spaced wave crests arranged at right angles to the shoreline [von Arx, 1962].

Although their conclusion was that cusp-spacing is not simply related to the period of the waves or the wavelength of low edge waves on a beach, Longuet-Higgins and Parkin [1962] uncovered some enlightening facts concerning cusps. They noted that the difference between the permeability of the material in the cusp horns and the bays resulted in a difference in the relative power of the swash to erode material from the bay and horn. The backwash tended to be reduced by percolation of water into the beach. Since the horns are more permeable than the bays, there is increased percolation in the vicinity of the horns as compared with the bays. Thus, the backwash and consequently the eroding power of the swash is reduced near the horns compared with that in the embayments.

They also found the presence of an impermeable layer of material present within a few inches of the beach surface. This layer was closer to the surface in the embayment than under the horns. Permeability measurements showed that the horns were more permeable than the embayments.

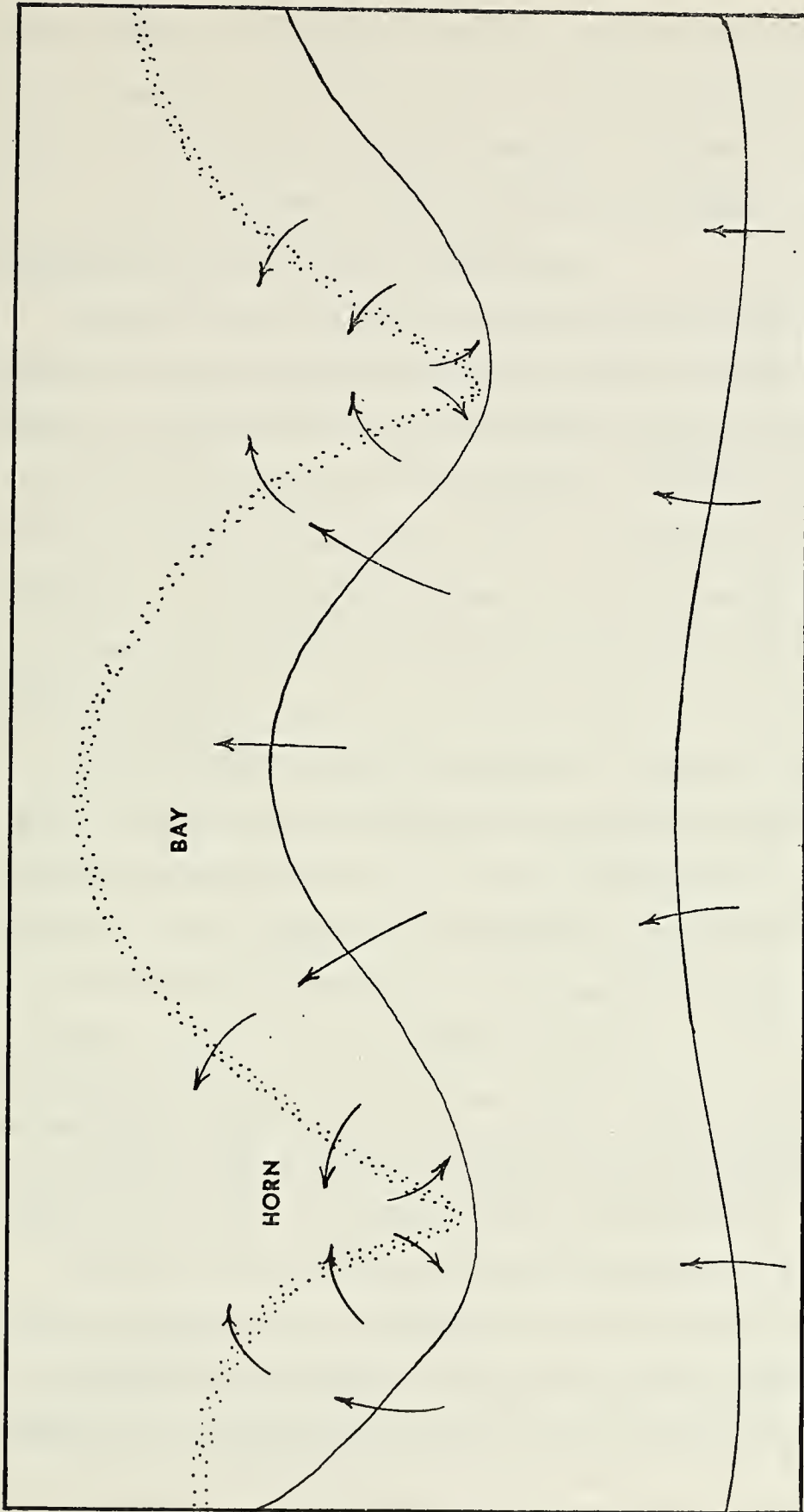


Figure 2. Diagram showing the Diffraction of the Swash as Proposed by Ph. H. Kuenen[1948]

Their studies also indicated that this permeability difference was due to the composition of the material. The horns consisted of coarse shingle, fairly well sorted, overlying an impermeable mixture of sand and shingle. In the bays, the surface layer of shingle was thinner. In some places the impermeable layer actually outcropped.

Longuet-Higgins and Parkin [1962] developed relationships between mean cusp spacing and wave period, wave height, and swash-length. Swash-length, as they defined it, was the width of the beach between the breaking point of the waves and the highest point reached by the swash, averaged over long-shore distance and over time. They found little relationship between cusp spacing and wave period. A close connection between wave height and an even better relationship between swash length and cusp spacing was obtained.

They believed that there was one other fundamental length of importance in determining cusp spacing. Two possibilities offered were the scale of the beach material or the length $(\nu^2/g)^{1/3}$ where g is the acceleration due to gravity and ν is the kinematic viscosity of the water.

The following conditions for the formation of cusps were specified by Longuet-Higgins and Parkin [1962, p. 199];

"(1) The incident sea waves were always normal to the beach and breakers were long-crested.

(2) The surface material was capable of being shifted freely by the waves but within a few inches of the surface there was always a compact and relatively impermeable layer of material."

Flemming [1964] conducted wave tank experiments in order to investigate the mechanism of the transport of particles during cusp formation. He concluded that, in general, each cusp was built on the remains of a predecessor. An impermeable layer was established soon after the swash

began to play over a beach. The initial waves eroded the beach surface and washed the fine particles down into the interstices of the underlying material to form an impermeable layer. Cusps then tended to form in the coarse material on top of the impenetrable layer.

Flemming observed a water movement pattern in the embayments similar to that shown in Fig. 3. This pattern differed from that observed by Kuenen [1948] but agreed with that observed by Russell and McIntire [1965], Longuet-Higgins and Parkin [1962], and this author.

Sorting of material by swash resulted in particles with a minimum settling velocity being found near the back of the bays. According to Flemming, the permeability of this mixture was low. Particles with slightly higher settling velocity accumulated on the cusps horns as a mixture of irregular particles having a higher permeability.

Russell and McIntire [1965] presented an enlightening article about beach cusps which supported the ideas of several early researchers. It was their belief that cusps were of a depositional nature, being deposits on pre-existing beaches. According to them, juvenile cusps began to form during a period of decreasing wave height following an erosional period caused by high waves. Cusps tended to originate and attain maximum development during transitions from winter to summer beach profiles. The cusps having the sharpest apical points seemed to occur where the impact of the waves was parallel to the shore. The more rounded apices developed if there were some longshore drift or slight departure of the wave fronts from a parallel alignment with the shore.

Russell and McIntire found that the material of which cusps were composed differed from that found on the underlying beach. The horns

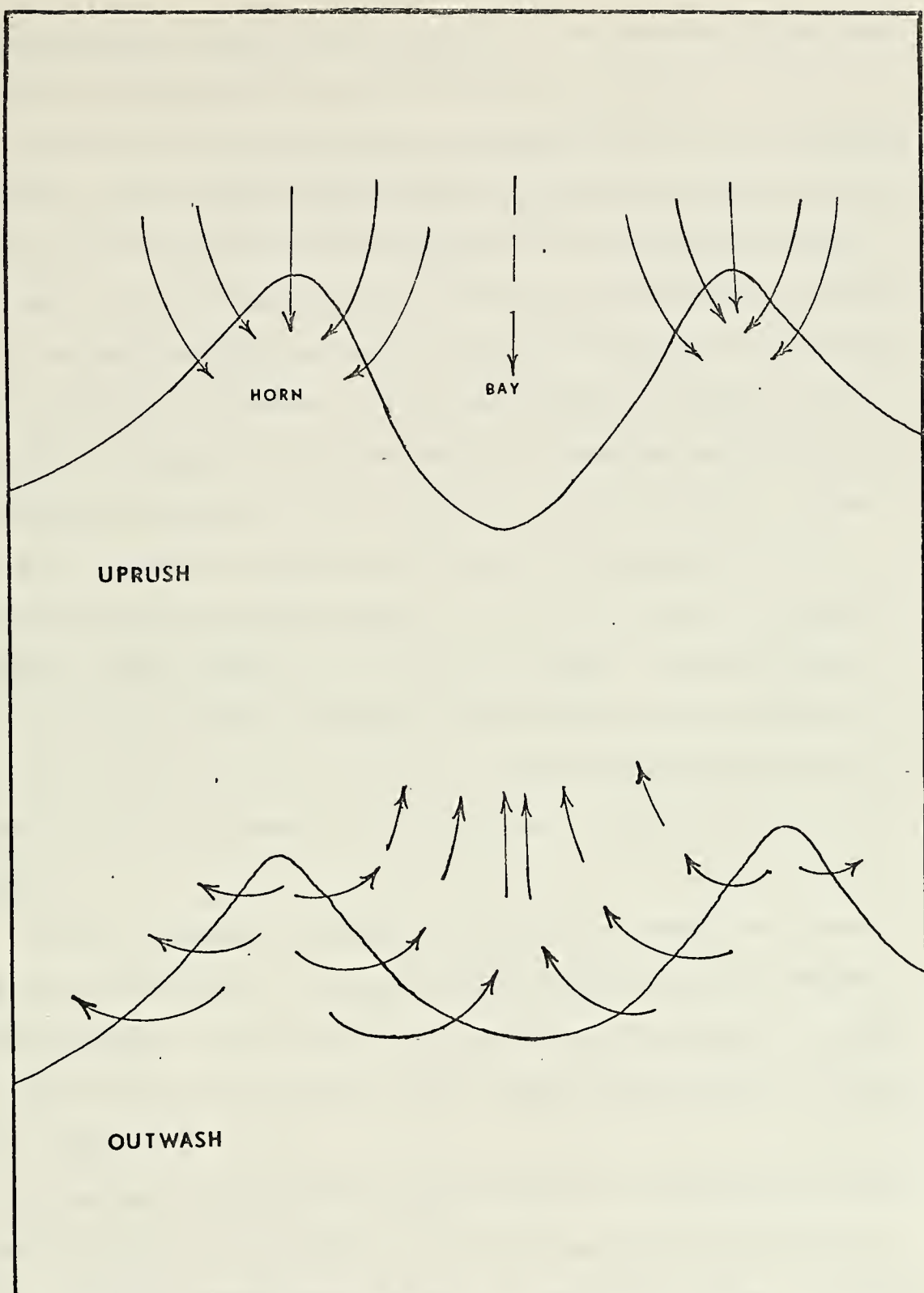


Figure 3. Typical Swash Pattern Observed in Beach Cusps. Similar Patterns in Mature Cusps Were Observed By Several Researchers and This Author.

were recognized as being areas of deposition. The material of cusp horns was found to be softer and coarser than that of the bays.

The authors did not specify why cusps began to form at one location or another. They simply supposed that cusp formation had begun at some location and described the events which lead to fully developed cusps. The swash arriving at the cusp horn divided and the water swept into the bays. Any material which was being carried by the upsurge which did not come to rest was carried away. Due to the decrease in turbulence and velocity of the water as it flowed around and sometimes over the horns, the heavier and coarser entrained material was deposited there. After the initial removal of loose material from the embayments, the water flowing back down the bays possessed transportation velocity to keep its suspended load in motion, but rarely was it capable of entraining new load across the bay-floor pavement. This pavement was initially established at the bottom of the bay when all loose materials had been removed by overflowing waters and was resistant to any further loss of material.

Juvenile cusps were irregular at first; two to three times larger than final cusp spacing. The regularity increased as the cusp became better developed. Cusp forming processes apparently succeeded in shifting the original horns so that irregular members became incorporated into larger members.

An unusual theory concerning cusp formation was suggested by Cloud [1966]. According to his theory, a breaking wave may follow Plateau's Rule. This rule, developed by the Belgian physicist Plateau, states that under gravity-free conditions a liquid cylinder becomes unstable when

its length exceeds its circumference. The cylinder then separates into nearly equal divisions whose lengths are proportional to the diameter of the cylinder. A breaking wave approximates a cylindrical form according to Cloud and breaks into segments which cause the formation of cusps. The ratio of the cusp length to wave height was 16 or 20 to 1, as documented by Cloud.

Dolan and Ferm [1968] proposed the idea that crescentic coastal landforms, such as the Carolina capes, represent only one order of shoreline forms in an uninterrupted hierarchical grouping of coastal features. Smaller forms were grouped within the larger forms with a logarithmic spacing between groupings. Their hierarchy of spacing is:

- (1) cusplet (4.9ft) (1.5m)
- (2) typical beach cusp (26-82ft) (8-25m) such as are examined in this study,
- (3) storm cusp (230-394ft) (70-120m), and
- (4) giant cusps or shoreline rhythms (2300-4920ft) (700-1500m)

Factors which Dolan and Ferm considered important in affecting cusp spacing were planetary currents, shoaling and breaking of waves, and eddy currents which produced the largest of the forms.

Bowen and Inman [1969] investigated the nearshore circulation of water on a plane beach exposed to a uniform wave train. The wave train when normally incident on the beach generated standing edge waves of the same frequency as the incoming waves. These edge waves interacting with the incident waves produced a steady circulation pattern consisting of on-shore flow toward the breakers, a longshore current in the surf zone, and an offshore flow in narrow rip currents. Bowen and Inman theorized that the combined flow associated with the incoming waves, the edge waves, and the nearshore circulation would rearrange beach sediment to produce a

regular longshore pattern of cusps. Sediment would be deposited in the surf zone by the slow onshore current. A rip current then tends to erode a channel for itself. The result of all this should be a system of beach cusps, whose spacing is equal to the wavelength of the nearshore circulation and dominant edge wave. At locations where the surf zone is wide and the slope of the beach small, the spacing of cusps is much smaller than the wavelength of the predominant edge wave. In such situations it seems likely that cusp formation is in response to the reformed wave, associated with the bore of the breaking wave, and edge waves traveling within the surf zone, which have a smaller modal number than that of the predominant flow pattern. No direct or quantitative measurements of cusp spacing as related to edge wave wavelength were presented by Bowen and Inman in support of this theory.

Brueggeman [1971] showed the depositional character of a single beach cusp horn [p. 36]. Also, the presence of buried cusp horns (shown by landward dipping layers) points to a depositional character.

II. DATA COLLECTION

A. COLLECTION PERIOD AND LOCATION

Data collection was accomplished during the winter months in order that the maximum number of changes in beach profile would occur. It is during periods of changing wave parameters such as the winter months that the beach goes through cycles of erosion and accretion. By making daily observations during this period it was hoped that a substantial number of opportunities to observe formation and destruction of beach cusps would occur.

Three data collection sites were chosen along Del Monte Beach for several reasons. First, there is a gradient of wave heights due to refraction from north to south with the largest waves at the north end. Thus cusp formation could be observed over a wide range of wave conditions. Unfortunately, no simple relationship existed between wave heights observed at various locations along the beach due to the changing refraction pattern associated with the incoming deep water wave angle and wave period. This necessitated taking wave height observations at all three observation sites vice just one.

A second reason for selecting Del Monte Beach was the existence of a gradient in sand sizes along the beach from north to south. At the north end of the beach near Holiday Inn, the sediment is a medium sand. At the south end of the beach, the sediment is a fine sand [Dorman, 1968].

There is essentially no longshore current present at Del Monte Beach [Dorman, 1968]. Additionally, dye markers placed in the surf at the beginning of this project confirmed this fact. The absence of a longshore current is caused by a very small breaker angle. Due to refraction, the

breakers arrive with their wave fronts almost parallel to the beach [Koehr and Rohrbough, 1964].

The upper beach as defined by Bagnold [1940, p. 30] also has a range of slopes, varying from 10-12 degrees at the north end to 2-3 degrees at the south end. This would be expected considering the north to south gradient in wave heights and beach sediment sizes.

Three locations along the beach were selected for obtaining cusp data (Fig. 4). These locations were at the upper end of the beach near the Holiday Inn, in the middle of the beach opposite the Navy Oceanographic Laboratory, and at the lower end of the beach. Henceforth, these locations will be referred to as the upper, middle or lower site.

These locations were selected due to the differences in wave height and sand grain size at the various locations while maintaining reasonably close proximity between sites to facilitate obtaining daily measurements. A distinct difference in cusp spacing, cusp depth, and frequency of cusp occurrence was observed at the three locations. A reference cusp was chosen at each site which initially was close to a reference point established by triangulation on the beach.

Daily observations at all three sites were planned so that short term changes in wave and beach parameters could be measured and recorded. The majority of the measurements were obtained at the planned frequency although extremely severe weather or some other unforeseen event occasionally precluded obtaining readings at the prescribed time. These lapses in the observation schedule were not considered to have seriously degraded the results of the project.

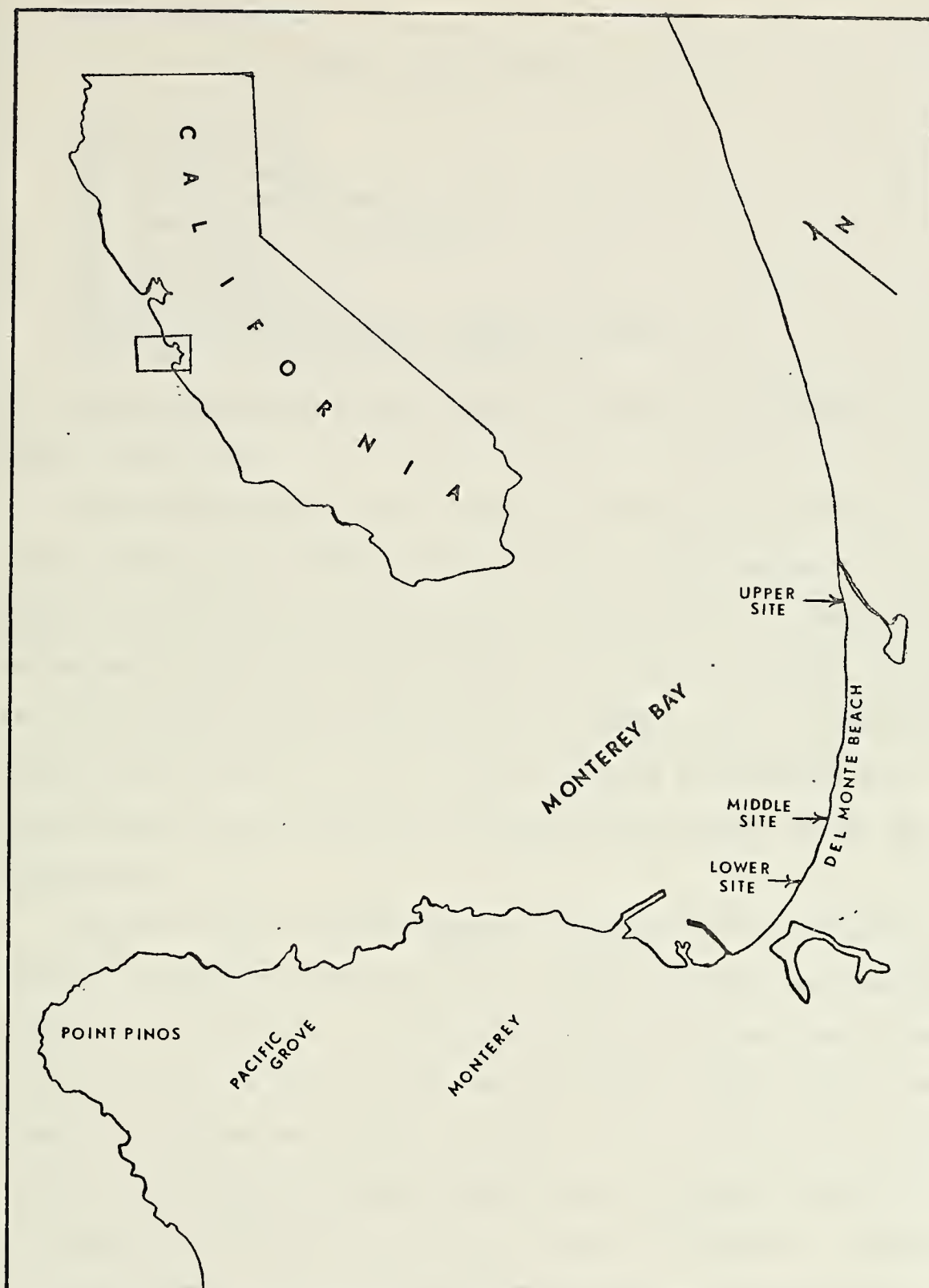


Figure 4. Locations of the Observation Sites Along Del Monte Beach on Monterey Bay.

B. PARAMETERS MEASURED

The following parameters were recorded daily (Fig. 5):

- (1) beach slope,
- (2) width of cusp,
- (3) depth of cusp,
- (4) width of swash zone,
- (5) movement of reference cusp,
- (6) wave height,
- (7) wave period,
- (8) tidal information,
- (9) depth of loose layer of material on beach, and
- (10) remarks and descriptive comments.

The cusp width was measured from horn to horn at a position on or close to the apices.

Cusp depth was measured approximately two-thirds of the distance from the apex towards the rear or shoreward edge of the embayment. The depth was measured by planting a ruled measuring pole in the center of the embayment approximately midway between the horns, and sighting from the top of one horn across to the top of the opposite horn. The height above the sand where this line of sight intercepted the measuring pole was considered to be the depth of the cusp measured relative to the top of the horns.

The slope of the beach was measured at the center of the reference cusp bay. Periodically, the beach slope at other locations was obtained. Slopes were measured using a large two armed protractor (each arm approximately 3 ft long) with the movable arm fitted with a bubble level. The fixed arm was placed on the sand, the movable arm was then raised until level as indicated by the attached bubble level. The angle between the two arms (the beach slope) was read from a large (1 ft diameter) protractor scale located at the pivot point of the two arms. The arms of the

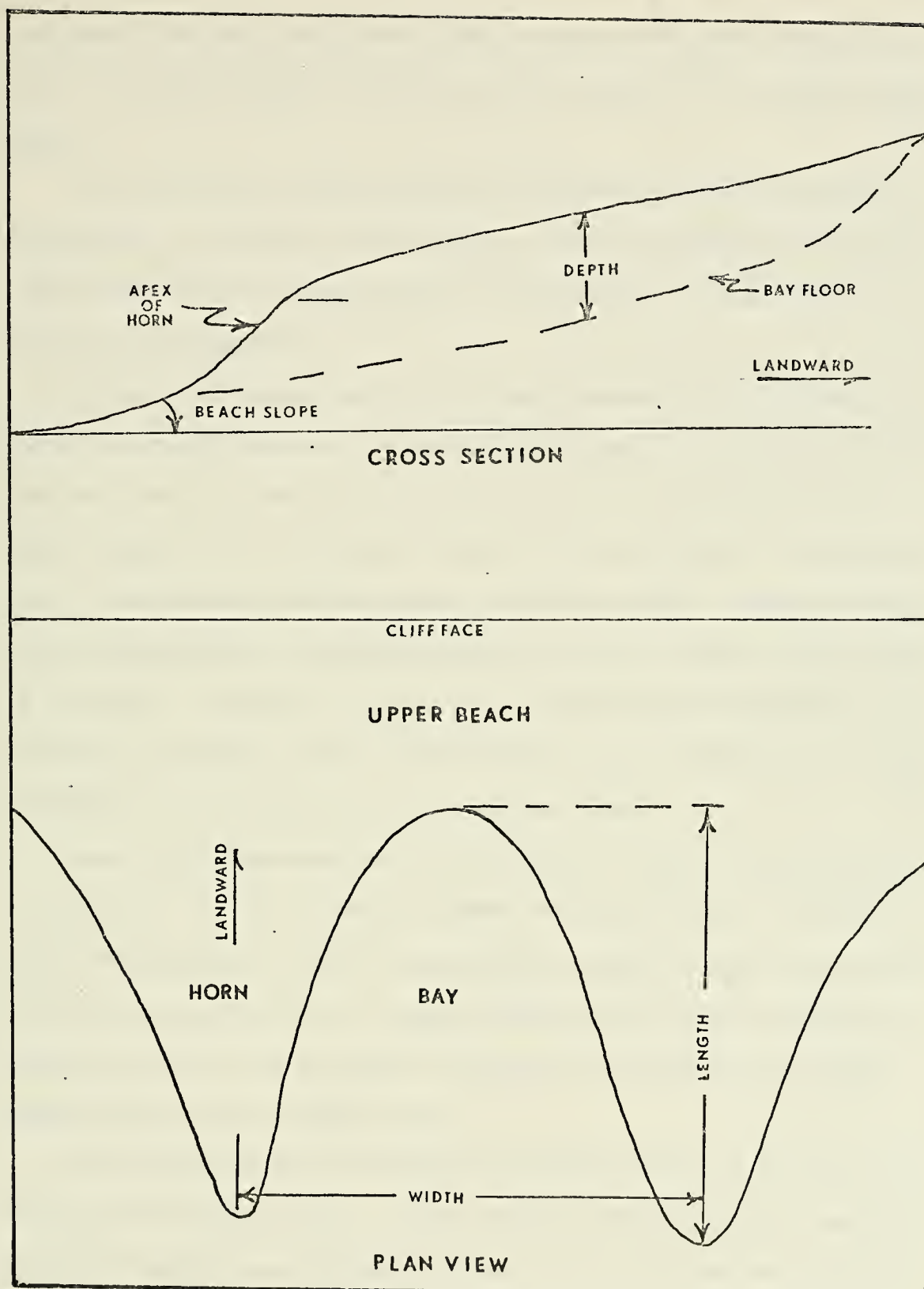


Figure 5. Description of the Parameters Associated With Beach Cusps.

instrument were made sufficiently long to smooth out small discontinuities in the beach profile and thus provide a measure of the average beach slope.

The swash zone as measured was the distance from the low level of the backwash to the upper level of runup. This measurement was only recorded when the tide level placed the swash zone in close proximity to the cusps being measured.

In order to measure migration of the reference cusp on the beach, a set of orthogonal axes with the origin positioned at a reference (fixed) location were used. Migration of the reference cusp laterally (long-shore movement) and transversely (onshore-offshore movement) was measured daily utilizing this two dimensional coordinate system. Using this system, the migration of a reference cusp was traced throughout the lifetime of the series. Whenever a new series of cusps formed following the destruction of an older series, one of the new cusps located near the reference point was selected as the new reference cusp.

Wave heights recorded were the significant heights of the breakers. The heights of 20 of the larger breakers were measured over a length of time corresponding to about 60 wave periods, using the wave pole method of measuring crest heights. These 20 breaker heights were averaged and then multiplied by $4/3$ in order to correct for depression of the wave trough below the still-water level.

The wave period was the average significant period or the period of the large well-defined waves. These periods were calculated by measuring the total elapsed time required for four or five of these larger waves to pass a distant point near the seaward edge of the surf zone. Time was

divided by one less than the number of waves observed to obtain an average period. This measurement was repeated until several average periods were obtained whose values were in good agreement.

The U.S. Coast and Geodetic Survey Tide Table information recorded daily were the times and heights of high tides. The tide range from lower low water to highest high water was also recorded.

An indication of the penetrability of the surface layer of the beach was obtained at each site by forcing the wave measuring pole into the beach using approximately the same force (body weight) on the pole each day. Penetration depth measurements were conducted on both bays and horns.

In addition to the daily observations, periodic measurements of several other parameters were found to be necessary. One such parameter was sand size. Samples for textural analysis were collected at selected times and locations.

Relative permeability measurements were also made. A plastic tube with a diameter of 2.62 in (.067m) and a volume of one liter was inserted into the beach at selected points. The time for one liter of seawater to drain into the beach under the influence of gravity was measured. The tube was inserted the same distance (approximately .015 in) into the beach each time the measurement was conducted. Due to the differences in tide level, water table height, amount of runup, etc., measurements obtained on different days and at different times of day probably are not directly comparable. Readings taken on the same day within the same time period can be compared directly.

Changes in the depth of the beach sediment were measured using a row of 11 stakes, approximately 2 ft high and 14 ft apart, aligned parallel to the beach. When the stakes were first positioned, the beach was barren of loose sediment following a winter storm. The distance from the top of each stake to the sediment layer on the beach was measured daily as sediment returned to the beach. Eventually a series of cusps were observed to form on the section of beach spanned by the measuring stakes.

III. DATA ANALYSIS AND PRESENTATION

A. CUSP WIDTH AS A FUNCTION OF MEASURED PARAMETERS

Multiple linear regression analysis of the data was performed using the BMD02R computer program developed for use at the UCLA Medical Center. This program computes a series of multiple linear equations in a stepwise manner. At each step one variable is added to the regression equation. The variable selected is the one which makes the greatest reduction in the error sum of squares.

The values of the data obtained each observation day were punched on computer cards and the regression analysis performed. The parameters of wave height, period, beach slope, reciprocal beach slope, wave height squared and cusp depth were allowed to remain free as independent variables. Cusp width was selected as the dependent variable.

The regression analysis was performed separately upon data from each observation site. The data from the lower beach site was determined to be too inaccurate with respect to wave heights to produce meaningful results. Wave heights at the lower site were on the average 1 to 2 ft in magnitude. Small errors in visually determining these wave heights produced a large percentage error in the data. For example, a 0.5 ft error in wave height at the lower site constituted a 25% error. At the upper site where the average waves were much larger (6.6 ft) a 0.5 ft error in wave height represented only a 7.6% inaccuracy. Similarly, a 0.5 ft error at middle beach represented a 12.5% error. For the above reasons, the data obtained at the upper site was considered to be the most accurate.

Due to the substantial percentage of error in wave height data at the middle beach and the close correlation existing between wave height and period, the regression analysis program showed a slight preference for wave period over wave height (wave period measurements were less prone to error). However, when the same analysis was performed on the data from the upper beach where a close correlation between wave height and period was also present, wave height was selected as the most important parameter in the regression equation. Since wave height measurements at the upper site were more accurate than at the middle site, the regression relationship developed from the upper site data was considered more accurate.

When wave period information was suppressed at the middle site, the results of the regression analyses for both upper and middle sites were in fair agreement. In both of these cases, wave height was selected as the primary variable, followed by beach slope.

The regression analysis was performed using both filtered and unfiltered data from the upper and middle site. The filtered data were more representative of waves and beach conditions at the time of actual cusp formation. The criteria utilized in selecting the data were;

- (1) The data represented the wave and beach conditions when cusps first appeared following a period when cusps were absent.
- (2) There was a significant change in the wave or cusp parameters during a period when cusps were already present.

Based on this analysis the regression equation containing the two variables which best fit the data is:

$$W = 80 + 7.4 H + 1.6S,$$

where W = cusp width in feet, H = significant breaker height at the time of cusp formation or modification in feet and S = beach slope in degrees.

In an attempt to find the best single parameter which would have the highest correlation coefficient, the parameters, H^2/S , H/S , H , H^2 , and H^m/S^n (m and n representing values between 0 and 4) were transgenerated and a regression equation for each parameter then calculated (H and S represent the same parameters as defined above).

The results of this analyses (Table I) indicate that H alone provides the best fit in a single variable regression equation. It also indicates that the slope of the beach cusp is a relatively unimportant parameter in determining variability of the data. The value of the regression coefficient for the wave energy, H^2 , was only slightly less than that of the wave height, H .

There is most likely at least one additional parameter important in describing the variability of cusp spacing. As pointed out by Lonquet-Higgins and Parkin [1962], cusp spacing is proportional to the width of the swash zone or wave height and one other parameter having the dimension of length. It is possible that this parameter is the mean grain size of the sediment on which the cusp is formed. Because the regression equation presented doesn't contain the additional linear dimensional term which was discussed, it is not considered to be a general equation which could be expected to be valid on any beach other than Del Monte. Due to paucity of sediment size data, this parameter was not included in the regression analyses.

TABLE I

TABULATION OF THE REGRESSION ANALYSES RESULTS

Parameters	Multiple Regress. Coefficient	Parameters	Multiple Regress. Coefficient
H,S	0.5659	m=2.2	0.4834
H ² , 1/S	0.5251	m=2.4	0.4813
H,1/S	0.5596	m=2.6	0.4781
P,1/S	0.5157	m=2.8	0.4743
P,H,1/S	0.6401	m=3.0	0.4701
P,H,S	0.5854	m=3.2	0.4655
H,D,1/S	0.6861	m=3.4	0.4608
D,P,1/S	0.6579	m=3.6	0.4560
H,D,S,P,1/S	0.7030	m=3.8	0.4511
H ² /S	0.4839		
H/S	0.4176		
H	0.5591		
H ²	0.5242		
P	0.4785		
The Following is a Tabulation of Hm/S Where;		The Following is a Tabulation of H ² /S ⁿ Where;	
m=.2	0.0183	n=.05	0.5242
m=.4	0.1566	n=.10	0.5240
m=.5	0.2267	n=.15	0.5237
m=.6	0.2841	n=.25	0.5224
m=.8	0.3666	n=1.2	0.4648
m=1.0	0.4176	n=1.5	0.4309
m=1.2	0.4484	n=1.8	0.3931
m=1.4	0.4667	n=2.0	0.3670
m=1.6	0.4771	n=2.5	0.3040
m=1.8	0.4822	n=3.0	0.2492
m=2.0	0.4839		

Where: H=Wave Height (ft), S=Beach Slope (degrees)

P=Wave Period (seconds), D=Cusp Depth (ft)

B. SEDIMENT ANALYSIS

Standard grain size analyses were performed on sediment samples with a one-half phi increment between each screen in the stack. Samples were washed in fresh water, dried, and shaken for 10 minutes on a ROTAP machine. Fraction weights were determined using an electronic balance. Folk and Ward [1957] size distribution statistics were determined and are tabulated in Table II.

C. RELATIVE PERMEABILITIES

The permeability measurements were normalized to provide a more meaningful analysis. An average permeability time (434.4 seconds) was calculated and divided by each individual time. Values greater or less than unity represent cases where the relative permeability is greater or less, respectively, than the average permeability. The values of normalized relative permeability are shown in Table III.

D. BEACH PROFILE

The differences between the thickness of sediment observed each day and the thickness of sediment initially covering the beach were calculated and plotted in Fig. 12 and 13.

TABLE II

SEDIMENT SIZE DISTRIBUTION STATISTICS FOR SAND SAMPLES TAKEN ALONG
DEL MONTE BEACH

<u>Sample Location</u>	<u>Date of Sample</u>	<u>Folk and Ward Mean Diameter (Phi Units)</u>	<u>Description</u>
Cusp bay, upper site	4/12/73	1.48	Medium Sand
Cusp horn, upper site	4/12/73	1.33	Medium Sand
Cusp bay, middle site	4/16/73	2.06	Fine Sand
Cusp horn, middle site	4/16/73	2.02	Fine Sand
Cusp bay, lower site	4/12/73	2.13	Fine Sand
Cusp horn, lower site	4/12/73	2.10	Fine Sand
Cusp bay, middle site	5/12/73	2.21	Fine Sand
Cusp horn, middle site	5/15/73	2.12	Fine Sand
Stake No. 11, middle site	5/ 8/73	1.96	Medium Sand
Stake No. 6, middle site	5/ 8/73	2.04	Fine Sand
Stake No. 1, middle site	5/ 8/73	2.10	Fine Sand

TABLE III

TABULATION OF RELATIVE PERMEABILITY MEASUREMENTS OF BEACH CUSP HORNS AND BAYS ALONG DEL MONTE BEACH

<u>Location</u>	<u>Sample Date</u>	<u>Relative Permeability</u>
Upper beach, bay	5/ 2/73	1.81
Upper beach, horn	5/ 2/73	2.95
Beach above cusp, upper site	5/ 2/73	1.95
Lower beach, bay	5/ 2/73	0.34
Lower beach, horn	5/ 2/73	0.47
Middle beach	5/ 8/73	
Stake No. 1		1.66
Stake No. 4		2.41
Stake No. 6		1.33
Stake No. 8		1.64
Stake No. 11		1.69
Middle beach, bay	5/15/73	.88
Middle beach, horn	5/15/73	1.03
Beach above cusp, middle site	5/15/73	.72

IV. DISCUSSION AND INTERPRETATION

A. CUSP FORMATION

A very critical balance of wave and beach conditions are necessary before cusps can form. Long periods exist, especially during summer months, when conditions are not favorable (as described below) for cusp development and none appear on the beach. Even when conditions appear to be ideal, cusps may not always form.

In order to determine if cusps were erosional or depositional features, two attempts to cause cusp formation were carried out. The first try, on 31 January, 1973, entailed digging a trench perpendicular to the shoreline 19 ft long and 1 ft deep to simulate a bay on a beach where cusps frequently form. All wave and beach conditions appeared to favor cusp formation but none were found. Again, on 2 February, 1973, an artificial ridge (or horn) of sand 22 ft long, 2 ft wide and 20 in high was constructed perpendicular to the shoreline on the beach. As in the first attempt, no cusps were induced to form. These results reveal the difficulty of inducing cusp formation. While it is probably possible to cause cusps to form, it would require a great number of trial and error attempts and a considerable amount of luck to be successful.

Based on the observations at Del Monte Beach, one important requirement for cusp formation is that a plentiful supply of loose and permeable sediment be present. This observation is in agreement with the idea that the surface material be capable of being shifted freely by the waves as specified by Longuet-Higgins and Parkin [1962] and with the observations of Fleming [1964], and Russell and McIntire [1965].

Another very important condition for cusp formation is the angle of the breakers as they approach the beach. Only when the wave fronts are nearly parallel to the beach can cusps form. In addition, from observations made along Del Monte Beach, it appears that long crested swell with a period of 14-15 seconds also enhance the development of cusps.

It appears that in the study area cusps form most often in the coarse, loose sediments such as those deposited on the beach following a winter storm. Although the winter season is usually an erosional period, the interval between storms is sometimes long enough for the sediment which has been carried offshore to be partially redeposited on the beach. There is a definite lag between the time of occurrence of a winter storm and the reappearance on the beach of the sediment which was moved offshore by the storm waves. It is in this first layer of coarse sediment that the initial formation of beach cusps is observed. This observation of initial cusp development is supported by the contention of Russell and McIntire [1965] that cusps form following a decrease in wave height.

Another condition which seems to be important in cusp formation is the requirement for a clean smooth beach. Heavy deposits of seaweed or debris appear to interfere with the water motions over the beach. Similarly the beach should have a fairly uniform slope without sharp discontinuities such as steep sided holes or ridges.

Cusps frequently commence formation at some location on the beach where accretion of sediment has taken place. This build-up may be due to either upper beach topography or some process occurring in the surf zone such as described by Bowen and Inman [1969]. Initially an embryo

horn is formed at the point of accretion with the rest of the cusp being developed later. As will be subsequently shown, cusp development is a progressive occurrence.

Under certain conditions where old or relic cusps have been left on the beach, new series of cusps can begin to form as a seaward extension of a previous cusp horn. The new series then propagates up or down the beach in much the same manner as will be described below. The cusps in the new series are spaced at intervals determined by the concurrent wave conditions. When the location of a horn from the new series is close to, but seaward of, a relic cusp horn, a connecting ridge may angle down from the relic horn towards the new horn forming a connection between the two.

Contrary to the theories of Jefferson [1899] and Evans [1938], cusps were not observed to commence formation on seaweed, debris or in a sand ridge. Frequently, following a winter storm, the beach was heavily littered with kelp torn from the sea bottom and various other types of debris. Not until these items were almost completely buried and the beach was relatively smooth were cusps observed to form.

Usually, cusps started to form near the high water position on the beach near a point of accretion. This depositional area on which cusp growth commenced was continually enhanced until the area was of sufficient height and width to visibly perturb the swash moving around and over the elevated area or rise. As the swash moved up the beach, the uprush of water slowed and frequently stopped on the sides of the embryo horn. On both sides of the rise the uprush continued further up the beach. This characteristic water motion can be observed in Fig. 6.



Figure 6. Characteristic Water Motion Near a Cusp Horn on Del Monte Beach.

The energetics associated with cusp development may be explained as follows: the kinetic energy of the uprush is dissipated by three major processes;

- (1) bottom friction
- (2) conversion of kinetic energy into potential energy due to an elevation increase, and
- (3) percolation losses into the sand.

It is easy to understand why the uprush slows and ultimately stops on the rise while it continues landward on both sides. The relatively steep sides of the rise or embryo horn causes an elevation of the water sweeping up its sides and a corresponding loss of kinetic energy by the water. The water moving landward on either side of the rise must travel a considerably greater distance up the beach profile before a comparable transition of kinetic to potential energy occurs.

In addition, as observed by Longuet-Higgins and Parkin [1962] and substantiated by the relative permeability values shown in Table III, horns are more permeable than bays. Thus more percolation of water into the beach occurs at the horns than in the bays. This reduces the erosional capability of the backwash in the vicinity of the horns.

Material being transported by the swash remains in motion either as bed load or in suspension as long as the velocity is sufficient to maintain a turbulent regime. As either velocity or turbulence of the water decreases, sediment is dropped, the heavier and larger material first. This process occurs both on the horns and in the bays. However, since the horns are more permeable and more of the uprush percolates into the beach, there is less backwash to return sediment back towards the surf. That material which is entrained again by the receding fluid is small in size, thus the heavier, coarser material remains on the horn. Kuenen [1948], Longuet-

Higgins and Parkin [1962], and Russell and McIntire [1965] also found the material in the horns to be coarser than in the bays. Table II shows the results of size analyses of the material from the cusp horns and bays.

The formation process discussed above is regenerative in that the higher the horn becomes, the more pronounced is the effect of the horn on the incoming swash. Additionally, as the tide level decreases, the horn building process progresses seaward developing a horn of considerable length, often extending midway down the beach face.

A small angle of incidence of the breakers or possibly just the presence of the horn itself modifies the upwash or surge. The water, instead of moving directly shoreward, swings in an arc across the beach face (Fig.7). This uprush of water tends to have more erosional capability than would be the case if no horn were present. The uprush of water divides around the horn and the flow is deflected to the right and left. This water erodes the loose material, depositing coarser material at the periphery of the arc and carrying much of the finer material seaward with the backwash. Because of the deposition at the outer edge of the swash arc, a second rise or embryo horn commences formation at a location on the opposite side of the arc from the original horn.

The process is mainly one of deposition. Loose material from the embayments and from sediments which were transported from the surf zone by the uprush is deposited either on a cusp horn or at the shoreward edge of the swash.

The width between horns at the time of formation depends upon wave height and at least one other parameter. As discussed previously, this missing parameter is likely to be the mean grain size of the sediment covering



Figure 7. Movement of Swash in Arc Within the Embayment of a Beach Cusp.

the beach. Ultimately it is the height of the great waves (those waves which are substantially larger than the significant breaker height) which determines the cusp spacing. Additionally, a series of large waves arriving with the proper phase sequence results in a maximum runup and the widest arc of swash between cusps. A series of waves of this nature could also be termed "great waves".

The time required for a cusp or a series of cusps to form can vary greatly. A whole series of cusps may progressively form in a few hours (less than 24) or require several days. The formation time is a function of how closely the wave and beach conditions approach the conditions listed above as necessary for cusp formation and/or the amount of sediment in motion in the surf zone.

The generation process continues up or down the beach laterally as long as no major obstacles or discontinuities are encountered either in the beach profile or in surf zone conditions.

As a complete cusp (two horns connected by a bay) is formed and the angle of incidence of the breakers approaches zero, the arc of water sweeping around the bay from one side meets a similar stream of water from the opposite side of the bay as shown in Fig. 3. The reinforced backwash formed by the joining of these two streams of water frequently reacts with and retards the uprush of water in this center area between the horns. After this stage has been reached, there is a small amount of shifting and equalization of distances between horns and depths of the bays until the ability of the swash to further erode the bay is nil.

The uniform width observed in a series of cusps is attributed to formation of the cusp series while essentially the same size waves are striking

the beach. A typical series of cusps had the following spacing; 28-40-47-46-42-46-43-40-40-44-44 paces (width of average pace, 2.5 ft). If a gradient in sand size or wave height occurs along the beach, one can expect a change in cusp spacing. If a cusp series propagates slowly, over a period of several days, and the wave heights change significantly during that period, then the cusp spacings in the series will vary. Increasing widths will occur with increasing wave heights.

Cusps grow serially as have been described above. They do not all appear simultaneously. The formation of the next cusp in the series depends upon the perturbation of the swash by a previously formed horn. Cusps were observed to form in this manner during the study. Specifically, during the period 20-23 February, 1973, cusps were observed propagating south to north along the beach. Again on 25 February, 1973, a cusp series was observed to propagate south to north at the middle site.

An experiment was conducted at the middle site in which the horn of one of a series of well formed cusps was smoothed off into the adjoining embayment (Fig. 8). Partial success was achieved in observing the reformation of the destroyed horn. The dislocated material was washed out of the bay and redeposited at the location of the original horn by the action of the swash. The experiment was hampered by the weather as severe local winds occurred on the morning on which the experiment was carried out.

Several of the ideas previously discussed were evident throughout the course of the above experiment. It was obvious that the cusp horns were areas of deposition. Heavy concentrations of seaweed collected at the seaward ends of the horns (Fig. 9). The arc of the swash which removed the material from the bay and reformed the horn is visible in Fig. 10.

The experiment was hampered due to the large wind waves which were generated by a local storm. Wind waves, in general, tend to mishape and have a destructive effect on cusps. This destructive effect is possibly a function on the high initial steepness ratios of wind waves as compared to those of swell.

B. MEASUREMENTS DURING THE FORMATION OF A CUSP SERIES

In another experiment conducted in early May a series of 11 stakes were driven into the beach in a line parallel to the beach as shown in Fig. 11. The distance from the top of each stake to the sand was measured daily. The results of these measurements are shown in Fig. 12 and 13.

When the stakes were first driven into the beach, it was barren of loose sediment. Winter storm waves had removed the upper layer of sediment from the beach approximately 10 days previously. The beach was smooth with the majority of the seaweed and debris either washed away or buried. On the second day of observation, a thick layer of sediment was deposited uniformly over the beach. Size analyses of this sediment and relative permeability measurements showed that this sediment was of a relatively coarse material. It was this layer of loose sediment which supplied the material for future cusp formation.

The differences in height between the initial (barren) beach profile and those existing on each observation day are plotted in Fig. 12 and 13. Curve No. 1 shows the change between the initial profile and that existing on the second day of observation; curve No. 2 shows the same parameter for the third day of measurement, etc.

By the third day an area of accretion had begun to form in the vicinity of stake No. 9. This area continued to be enhanced throughout the



Figure 8. Destruction of a Cusp Horn at Del Monte Beach.

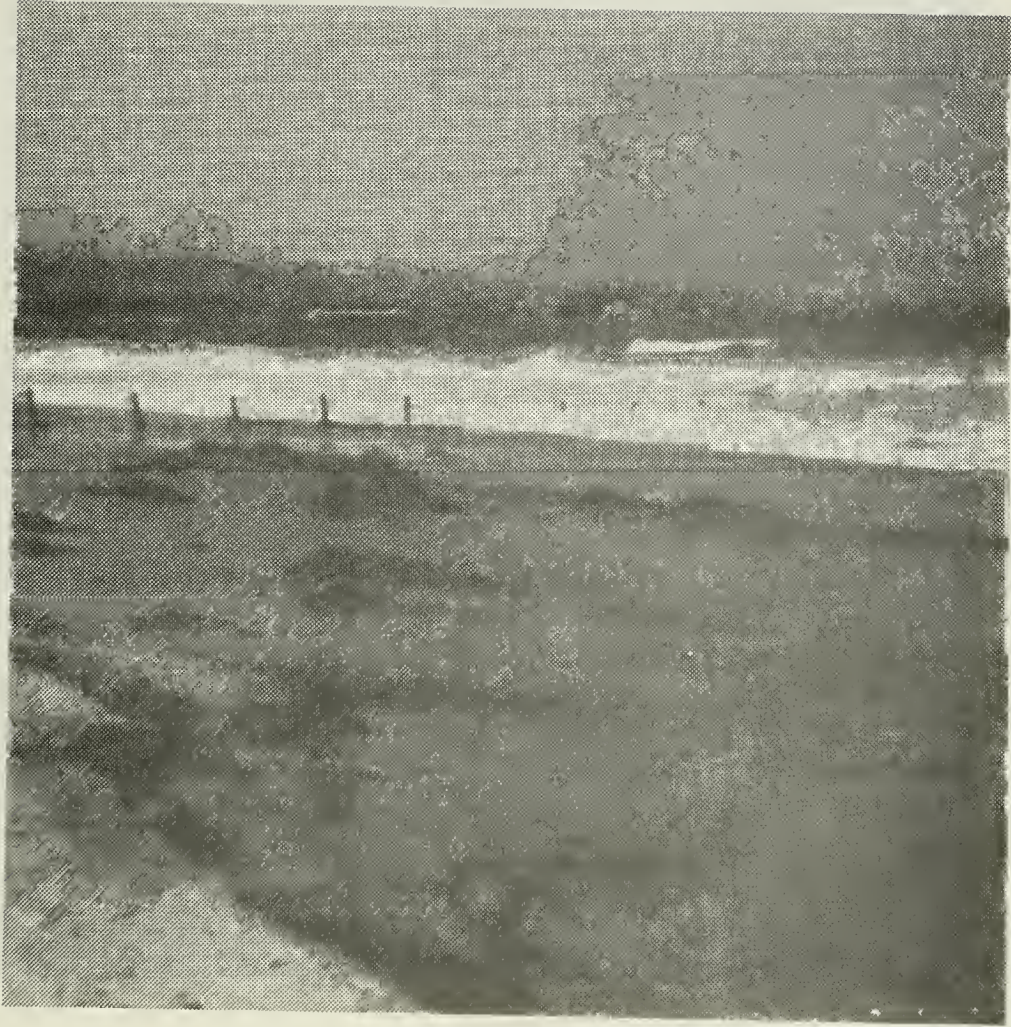


Figure 9. Collection of Seaweed at a Horn Apex on Del Monte Beach.



Figure 10. Arc of Swash Removing Loose Material from the Bay and Rebuilding of the Horn.

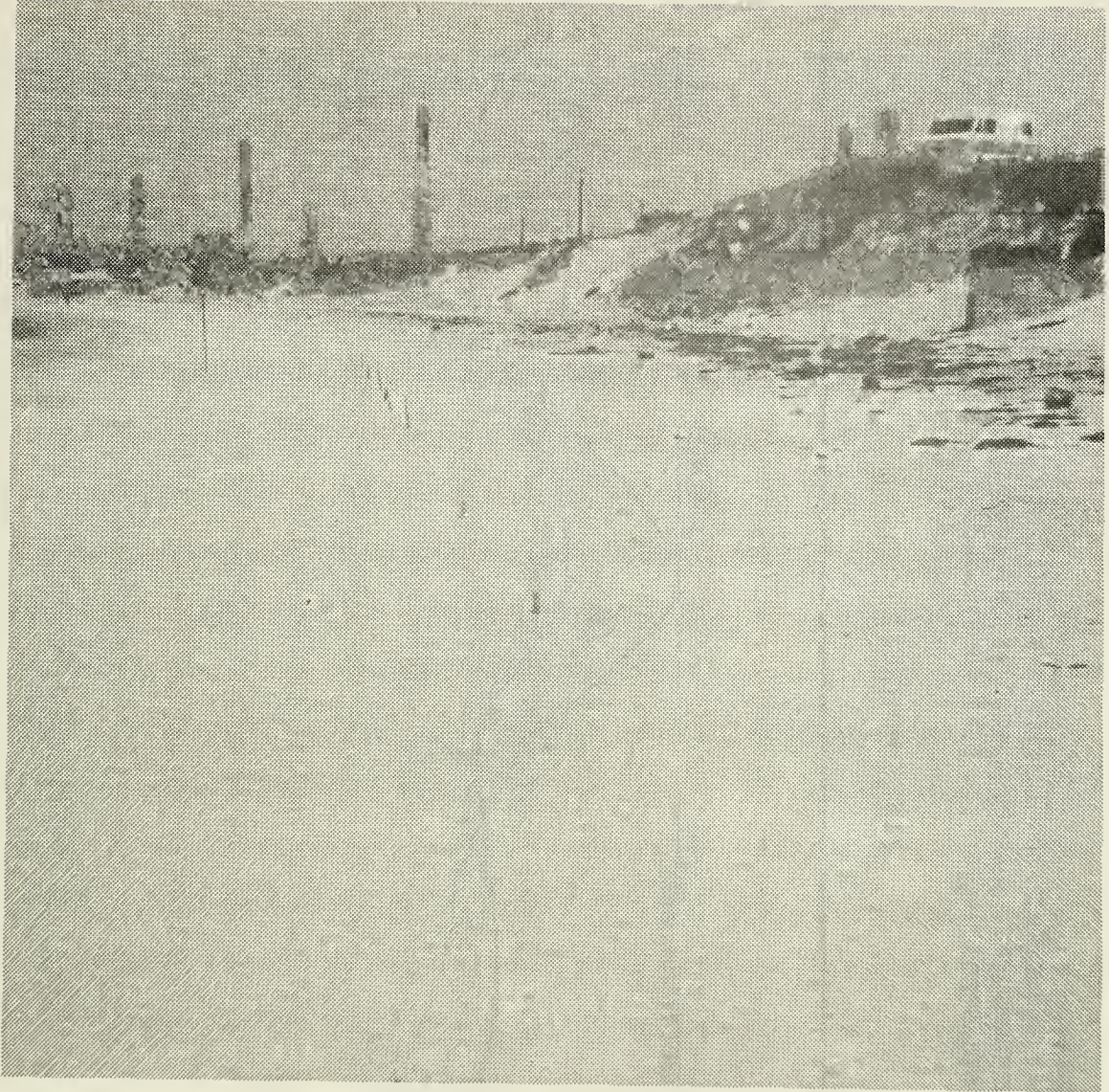


Figure 11. Row of Measurement Stakes Embedded in Del Monte Beach.

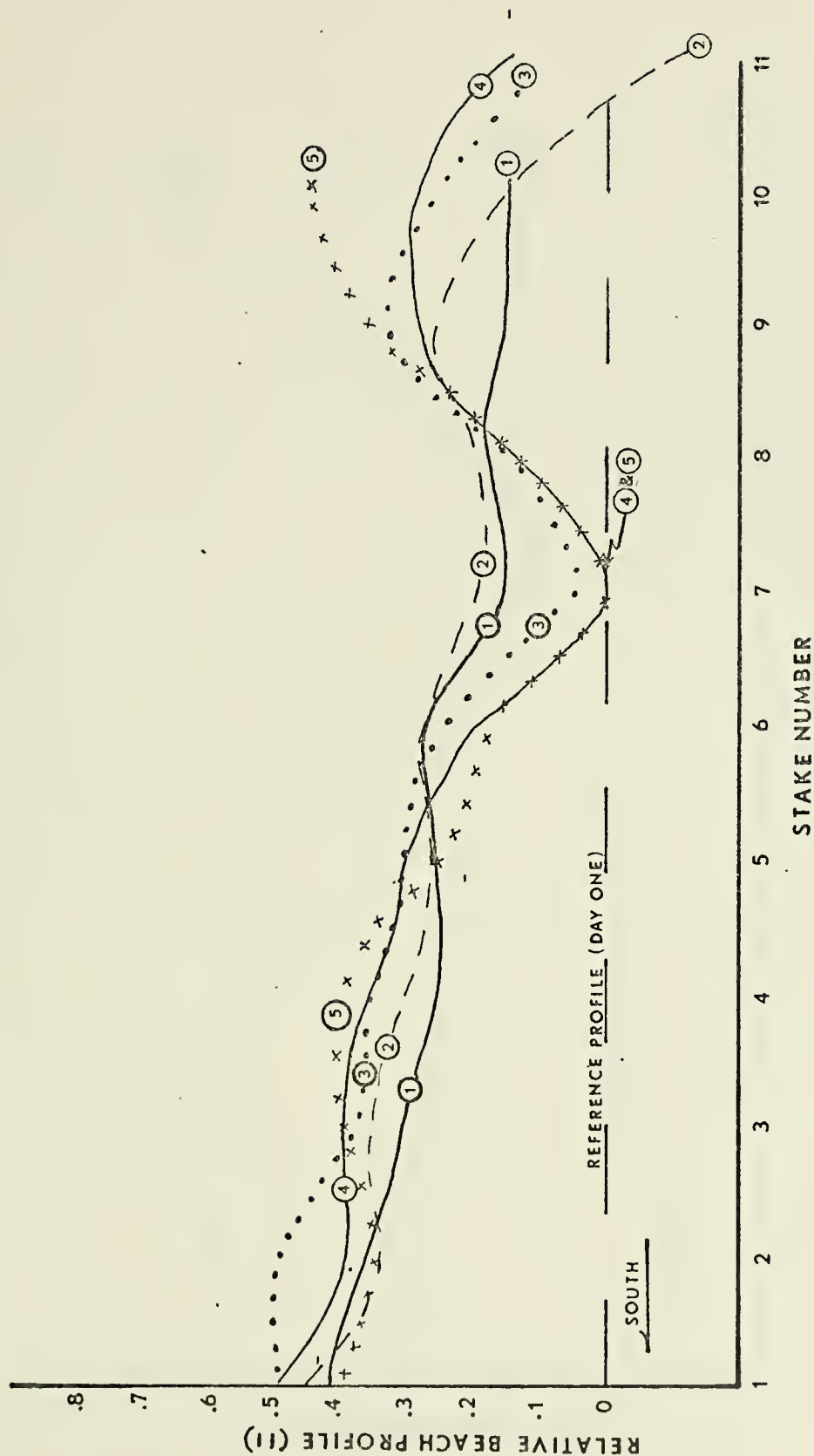


Figure 12. Relative Beach Plot for Days One Through Five of Beach Sediment Depth Measurements. Reference zero is the initial level of the beach. Curve No. 1 represents the thickness of the sediment supply available for cusp formation.

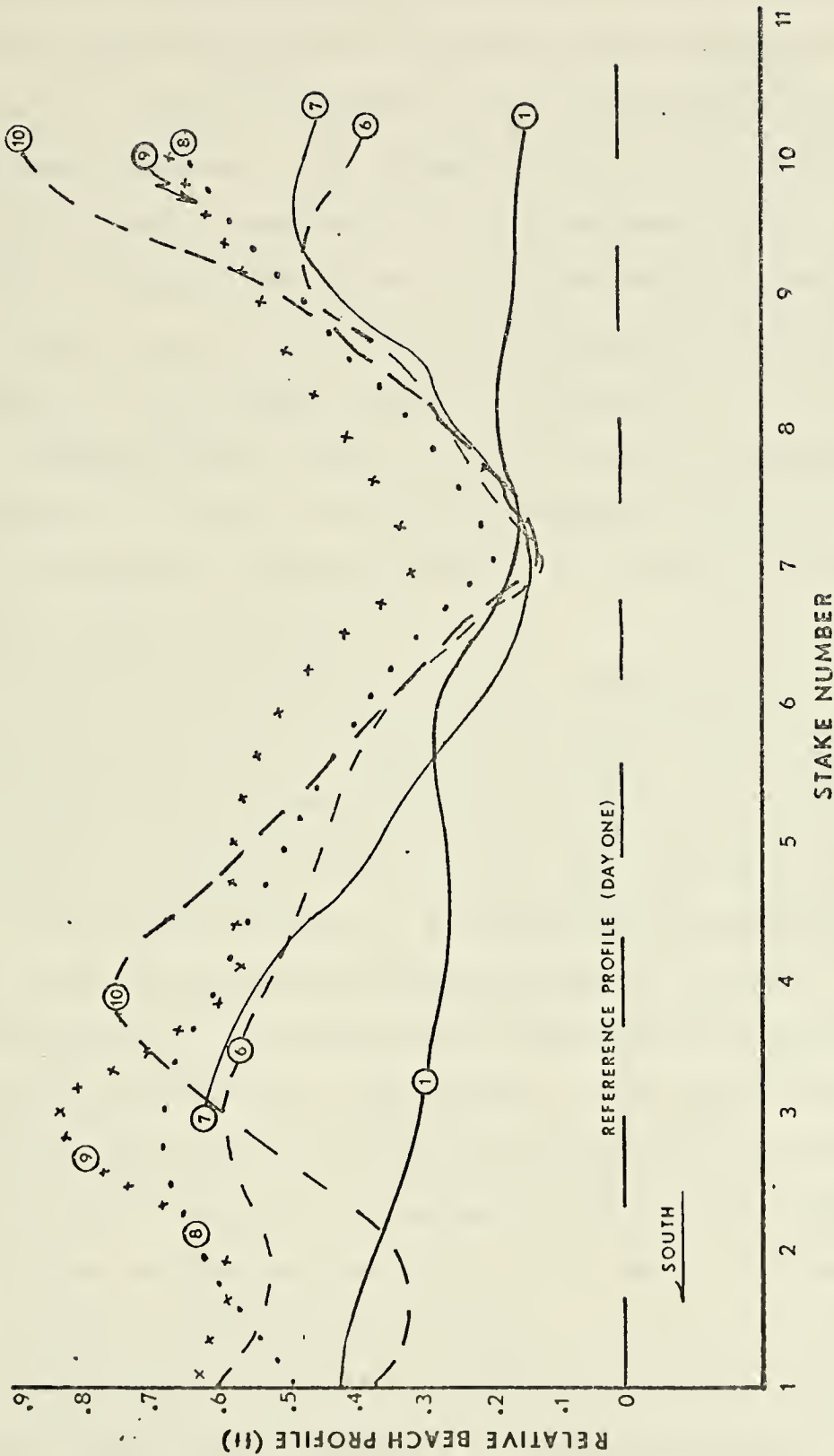


Figure 13. Relative Beach Profile Plot for Days Six Through Ten of Beach Sediment Depth Measurements. Reference zero is the initial level of the beach. The distance between stake No. 1 and No. 11 is 140 ft. The difference in relative beach height (difference between curves No. 10 and No. 1) shows the depositional character of cusp formation.

experiment, becoming initially a rise, then an embryo horn and finally, a fully developed cusp horn. The area of accretion was the starting point for a series of cusps which initially propagated north away from the measuring stakes. Later, probably due to a change in the breaker angle, the series propagated south in the measurement zone. The cusp heights indicated in Fig. 12 and 13 represent heights at the location of the measuring stakes and are not the maximum heights attained as the stakes were located towards the rear of the cusps.

An embayment began to form on the third day with the center near stake No. 7. Erosion of this bay and accretion at the horn near stake No. 9 continued as indicated by curve No.3. Little change occurred in the vicinity of stake No. 1-5.

On day five (curve No. 4), the start of development of a horn was visible near stake No. 3. Additionally, a layer of finer beach material was deposited over the beach between days five and six as indicated by the uniform increase in profile height of approximately 0.2 ft.

By day eight (curve No. 7), a definite horn had developed near stake No. 3 with an embayment being generated south of stake No. 1. Between days eight and nine, another layer of finer material arrived on the beach, enhancing and smoothing the cusp profiles. This process of finer material changing the outlines of the initially formed cusps had been noted in many previous instances. The tendency is for the finer sediment to smooth or obscure the sharp profiles of the initial cusps. This process can be referred to as "defocusing" of the cusps.

During days No. 10 and 11, a combination of continued sediment deposition and slight reorganization of the series occurred. By day No. 11

(curve No. 10) the series had reached equilibrium and showed somewhat smooth or defocussed profile of mature beach cusps.

It should be noted that the height of accretion of the horns above the initial level of coarse sediment (difference between curve No. 10 and curve No. 1) is greater than the depth of erosion of the bay below this initial layer. This supports the contention that cusp formation is primarily a depositional vice on erosional process.

C. CHANGES OCCURRING DURING THE LIFETIME OF CUSPS

The spacing of cusps is determined initially by the wave heights at the time of formation. A significant change in wave heights is required to alter the spacing of the cusps after formation. For example, at the lower site, the spacing of the cusps changed from 54 ft to 112 ft following a change in significant breaker height from 1.5 ft to 2.5 ft.

The cusp shape may be altered slightly from a sharp, well defined crescentic shape due to defocussing. Defocussing is caused by the deposition of fine sediments over the beach following initial cusp development. In addition, the porosity of the horns and bays decreases greatly when the finer material collects over the beach.

As frequently happens, wave heights may decrease to very low values following cusp formation and before the forerunners from the next winter storm approach. During this time, the spacing of cusp series tends to decrease.

The maximum depths of the cusps do not vary much once they have reached maturity. Once the erosion of the bays progresses to pavement level (that level of beach below the loose permeable sediment) no further

erosion occurs [Russell and McIntire, 1965]. Any depth changes which occur are a result of deposition or erosion of the horns or a uniform deposition of fine material over the entire beach. The latter occurrence frequently takes place soon after the formation of the cusp series.

A change from the nearly perpendicular angle between wave crests and beach or the presence of severe local winds may cause truncation or asymmetry of the horns. The axes of the horns are then no longer perpendicular to the shoreline, but are skewed at some angle. Wind waves may also cause scarping of both horns and bays.

Occasionally, one may see a new series of cusps form seaward of an existing series. This is especially prevalent when existing cusps have been cut back to near the top of the upper beach berm by storm waves and high tides. These storm waves and high tides widen existing cusps and reposition them landward on the beach profile.

Waves which are very much smaller than those which initially cause cusp formation may cause juvenile horns to begin to form. These new horns are usually centered midway between the older horns. A new series then forms whose spacing is nearly one-half of that of the original series. As an example, during the period of 4-6 April, 1973, the significant breaker height decreased by a factor of four and cusp spacing decreased from 134 ft to 54 ft.

Once cusps establish their positions on the beach, they tend to remain very stable, the horn positions shifting only a few feet over their lifetime.

D. DESTRUCTION OF CUSPS

In general, wind waves tend to truncate and destroy cusps. Cusps are also obliterated by very large breakers washing over the cusp site. If not completely destroyed, cusps may be driven to the back of the beach into the storm berm where they become large, mishapen storm cusps.

Very high tides and/or storm surges can remove nearly all sediment from the beach. Erosion continues until all loose sediment is removed and there is no material left to form cusps. Only after wave heights decrease and sediment is returned to the beach can cusp formation commence again.

V. SUMMARY AND CONCLUSIONS

The spacing between horns of a beach cusp is a function of the height of the great waves breaking at the time the cusp is formed. Wave height was determined to be the single most important parameter in describing the variability of beach cusp spacing.

The formation of beach cusps is a complex process. The conditions for formation are critical and a delicate balance of wave height, breaker angle, beach slope and sediment size must exist before cusp formation occurs. Initially, a supply of loose permeable material overlying an impermeable layer is required. The waves must approach the beach with a nearly zero breaker angle. Additionally, long-crested waves with a period of 14-15 seconds enhance the development process. The beach must be smooth and relatively clear of debris. The slope of the beach should be continuous with no sharp discontinuities.

Cusp formation is essentially a depositional process. It starts with the deposition of sediment which has been entrained in the swash, at a rise or area of accretion on the beach. As this area is built-up, it perturbs the swash causing the erosion of an embayment and the formation of a new rise or horn. Erosion of the embayment continues until the smooth impermeable pavement is reached. Thus, all the cusps of a series are not formed simultaneously, but develop sequentially.

The formation process results in the horns being composed of coarser, more permeable material than the embayment or surrounding beach. The increased permeability of the horn in turn aids the formation process by causing greater percolation losses of kinetic energy from the swash over the area of the horns than in the bays.

The uniformity in the width of a series of cusps is essentially a result of the fact that the same size waves were present at the time of formation of all the cusps. If a gradient in wave height or mean sediment size occurs along the beach, then a gradient in cusp spacing can be expected with the larger cusps associated with the area of greater wave height.

A change from the nearly perpendicular angle between wave crests and the beach or the presence of severe local winds may cause truncation or asymmetry of the horns. Wind waves may also cause scarping of both horns and bays.

In order to change the spacing of a cusp series once it has formed, a large change in wave height is required. Wave heights must change by approximately a factor of two before a change in cusp spacing occurs.

Cusps tend to maintain the same position as at the time of initial development migrating only a few feet during their lifetime.

Cusps are destroyed by prolonged exposure to large wind waves or very large breakers which wash over the cusp site removing the accumulated sediment. Very high tides and/or storm surges are also effective in removing sediment from the beach. If erosion continues until all loose sediment is removed, cusps cannot reform until conditions are altered to permit deposition of sediment.

VI. RECOMMENDATIONS

Additional study of the origin and development of beach cusps is necessary in order to develop universal relationships among cusp, beach and wave parameters. Further observation of the cusp forming process is needed in order to quantify the conditions necessary for cusp formation. Additional refinements of the theory of cusp formation should be developed.

At least two observation sites should be selected. The sites should be as dissimilar with regard to breaker characteristics, wave height, beach slope and sediment size as possible, and still permit frequent cusp formation such that sufficient opportunities to observe the formation process will occur. In this regard, observations should be made during the winter months.

Capacitance, resistance or a similar type of wave gage should be used in order to obtain accurate wave height readings. A rapid method of analyzing the wave records obtained such as the cumulative frequency distribution method would decrease the time to process each wave record.

Only when cusps are in the process of forming or when some significant change in wave or beach conditions occurs is it necessary for measurements to be taken. When observations are made, in addition to the daily measurements, relative permeability measurements and sand samples from the bays and horns should be obtained. The sediment analyses should be performed in one-quarter phi size steps instead of one-half phi size increments. This will add significance to the mean sediment size data.

At both observation sites, a grid of measurement stakes should be constructed. These stakes should be made of metal strong enough to withstand the wave energy of winter storms. Each stake should be labelled with a tag indicating its purpose to minimize vandalism. The stakes should be arranged in at least three parallel rows each at a different distance from the water. The length of the rows should be at least two cusp widths in extent. Sediment depth data should be obtained from this grid whenever cusps are forming within its boundaries. If possible, the swash zone parameter as defined by Longuet-Higgins and Parkin [1962] should be obtained daily when other cusp observations are being taken.

Using the above measurements, a more refined regression analysis can be performed with mean sand diameter and Longuet-Higgins' swash zone parameter as two of the variables considered.

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20.

It was determined that beach cusps are depositional in nature, forming most easily in coarse, loose sediment. Cusp development commences at a rise or area of accretion on the beach. A series of beach cusps forms sequentially rather than simultaneously.

The width of beach cusps are a function of wave height; the larger the waves producing wider cusp spacing. Uniform spacing of cusps in a series can be attributed to the same size waves striking the beach during the formation period of the cusps.

Once formed, cusps are stable and tend to maintain their dimensions unless a large change in wave or beach condition occurs.

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